THE IMPACT OF CLIMATE CHANGE ON THE GEOGRAPHICAL DISTRIBUTION OF *TRIPLOSTEGIA GLANDULIFERA*, A HIGH-ALTITUDE MEDICINAL PLANT IN CHINA

WANG, H. M.[1#] – NIE, M.[1#] – PENG, C.[1#] – XIONG, D. L.[1] – DONG, F. W.[1*] – HUANG, B.[1,2*]

[1]*Yunnan Key Laboratory of Southern Medicinal Utilization, Yunnan Key Laboratory of Chinese Medicine Processing, College of Chinese Materia Medica, Yunnan University of Chinese Medicine, Kunming 650500, China*

[2]*School of Pharmaceutical Sciences, Hunan University of Medicine, Huaihua, Hunan 418000, China*

[#]*These authors contributed equally to this work*

**Corresponding authors*
e-mail: dongfawu085@163.com; huangbin@hnmu.edu.cn

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Abstract. *Triplostegia glandulifera* is an alpine medicinal plant endemic to the Himalaya-Hengduan Mountains region, and its survival is currently threatened by climate change. This study utilized 176 valid distribution points and 37 environmental variables to predict the potential geographic distribution patterns of *T. glandulifera* under current and future climate scenarios (SSP126 and SSP585) using the MaxEnt model and ArcGIS spatial analysis techniques. The results indicate that the model's predictive accuracy is excellent (AUC = 0.939 ± 0.024). The dominant environmental variables influencing species distribution include annual precipitation (BIO_12, 612.3 ~ 1262.3 mm), elevation (Elev, 1618.4 ~ 4227.0 m), mean temperature of the wettest quarter (BIO_7, 22.2 ~ 31.2°C), and mean temperature of the coldest quarter (BIO_11, -4.8 ~ 10.3°C). Currently, highly suitable habitats are concentrated in the southeastern edge of the Hengduan Mountains and the Tibetan Plateau. Under future climate scenarios, suitable habitats are projected to migrate northwestward to higher elevations, exhibiting an "expansion-retraction" response characteristic under the SSP585 pathway. This study reveals the ecological adaptation mechanisms of alpine plants to climate change and provides a scientific basis for the conservation and climate adaptation management of *T. glandulifera*.
Keywords: *MaxEnt, ArcGIS, centroid migration, climate adaptation management*

Introduction

The alpine ecosystem, characterized by its steep environmental gradients, unique biodiversity, and high levels of endemism, is considered one of the most vulnerable ecosystems globally (Dong et al., 2022). Climate change is driving alterations in species distribution patterns, with upward migration to higher altitudes becoming increasingly common (He et al., 2019b; You et al., 2018). Such changes often accompany local contractions in distribution ranges (Vidal Junior et al., 2025), posing a serious threat to global biodiversity. Notably, high-altitude regions are experiencing warming at a rate that significantly exceeds that of low-altitude areas (Zhang et al., 2022). Additionally, as elevation increases, high-altitude habitats are gradually diminishing, similarly to submerged islands, which severely limits the available ecological niches for plants (Seastedt and Oldfather, 2021). This habitat reduction and dispersal limitation render alpine plants particularly susceptible to climate change, with some high-altitude species already exhibiting range contractions and population declines, and even facing the risk of

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"mountaintop extinction" (Rumpf et al., 2018; Watts et al., 2022). The Qinghai-Tibet Plateau and surrounding mountain ranges (especially the Hengduan Mountains and the Himalayas) represent the largest plateau mountain system in the world (Wang et al., 2025b), boasting the richest temperate alpine flora (Wang et al., 2025b) and serving as a critical biodiversity hotspot (Wei and Wang, 2025). The rate of warming in this region over recent decades has far surpassed the global average (Cui et al., 2018), raising significant concerns regarding the survival of its endemic plant communities (He et al., 2019a).

Triplostegia glandulifera is a representative alpine plant primarily distributed in the Himalaya-Hengduan region and Taiwan, commonly found in understory, streamside, or meadow environments at elevations up to 4000 m (Zhang et al., 2024). As a medicinal plant, its tuberous roots are traditionally used for treating kidney diseases (Guo et al., 2024). Modern pharmacological studies indicate that the polysaccharide components of *T. glandulifera* can regulate dyslipidemia and mitigate oxidative stress levels in the kidneys (Guo et al., 2024). Although *T. glandulifera* is not currently classified as an endangered species, it faces a survival crisis characterized by "the complete loss of habitat" due to the high sensitivity of its alpine ecosystem to climate change (Zhao et al., 2025). Therefore, based on its medicinal value, special geographical distribution, and the risk of having "the complete loss of habitat", proactive habitat conservation and population monitoring efforts are urgently needed for this species to address its potential extinction risk.

Species distribution models (SDMs) are widely utilized to associate species occurrence data with environmental variables, thereby predicting the probability of species presence (Elith and Leathwick, 2009). These models play a critical role in conservation strategies for endangered species (Landau et al., 2022). Among the most popular and extensively applied tools in the field of species distribution and niche modeling is the Maximum Entropy (MaxEnt) model, which outperforms various single-algorithm methods when dealing with presence-only data and maintains high predictive accuracy even with limited sample sizes (Morales et al., 2017; Vollering et al., 2019). Furthermore, its output can rival that of ensemble methods that utilize multiple algorithms (Zhao et al., 2025). The MaxEnt model has been successfully applied in the niche analysis of high-altitude plants, particularly in the Tibetan Plateau region (Shi et al., 2021; Qin et al., 2025).

Considering this background, the present study focuses on *T. glandulifera* as the research subject, integrating the MaxEnt ecological niche model with ArcGIS spatial analysis techniques. This study aims to address the following scientific questions: (1) What are the dominant environmental drivers influencing the geographical distribution patterns of *T. glandulifera*? (2) How do the suitable habitat migration trajectories and spatial reconstruction patterns of *T. glandulifera* evolve under two climate scenarios, SSP126 (sustainable pathway) and SSP585 (high-emission pathway), during the 2050s and 2090s? By elucidating the response mechanisms of this alpine plant to climate change, this research aims to provide a theoretical basis and practical guidance for establishing a dynamic monitoring system for *T. glandulifera* resources, formulating targeted conservation strategies for wild populations, and enhancing its medicinal cultivation efficiency through the regulation of dominant environmental factors.

Materials and methods

Species distribution Information

Distribution records of *T. glandulifera* were sourced from three major biodiversity databases: the Chinese Virtual Herbarium (CVH; http://www.cvh.ac.cn), the National

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Specimen Information Infrastructure (NSII; http://www.nsii.org.cn/2017/home.php), and the Global Biodiversity Information Facility (GBIF; https://www.gbif.org/). Using ArcGIS 10.8, the geographical coordinates associated with each specimen were carefully reviewed and standardized. To reduce potential spatial autocorrelation, the "Spatially Rarefy Occurrence Data for SDMs" tool within SDM Toolbox was employed to filter out records located within a 5-km radius of one another (Wang et al., 2025a). This process yielded a final set of 176 spatially independent occurrence points, which were used in subsequent modeling analyses (*Fig. 1*).

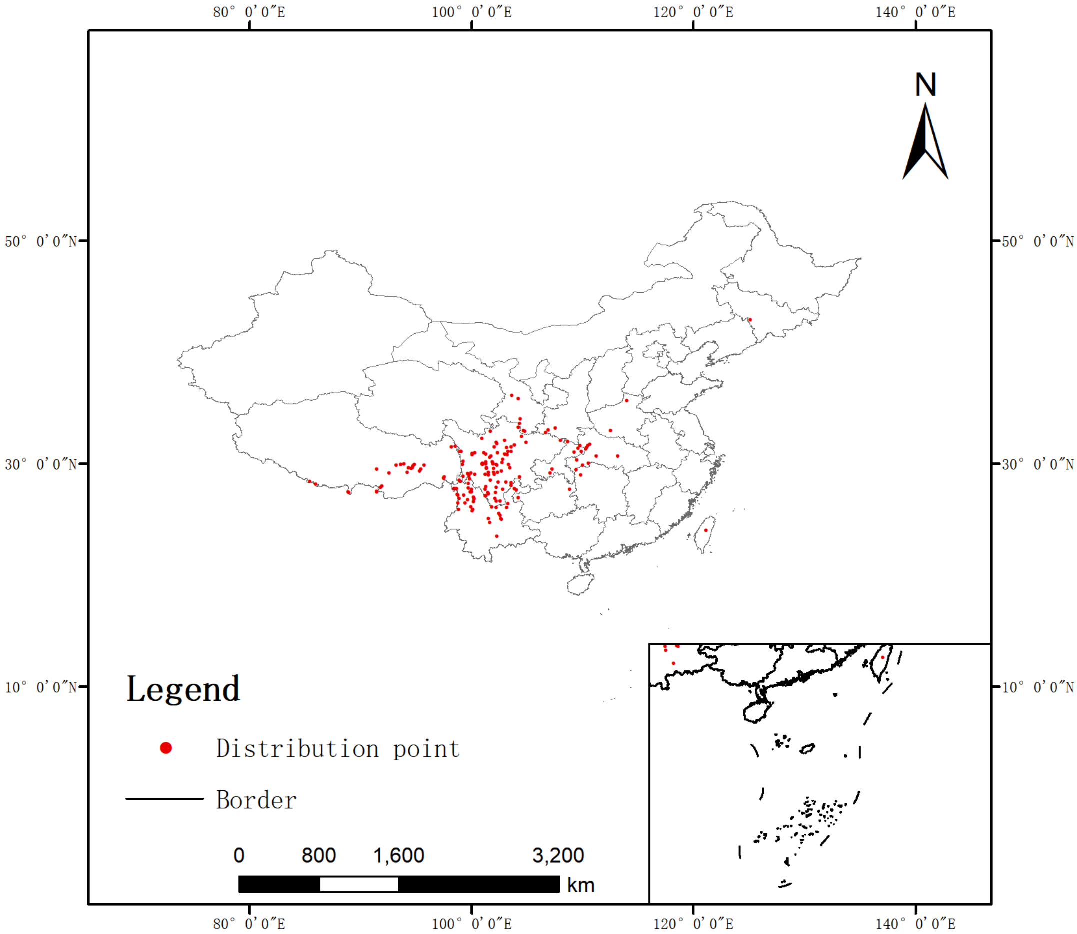

Figure 1. *The actual distribution points of T. glandulifera*

Environmental variables

This analysis integrated three categories of habitat variables for *T. glandulifera*: bioclimatic (19 variables), soil-related (15 variables), and topographic factors (3 variables), totaling 37 environmental variables. Historical bioclimatic data (1970 ~ 2000), along with future climate projections, were sourced from WorldClim (http://www.worldclim.org) at a spatial resolution of 2.5 arc-minutes. Future climate scenarios were derived from the BCC-CSM2-MR model—recognized for its reliability in simulating Chinese climate patterns—for the 2050s (2041 ~ 2060) and 2090s (2081 ~ 2100) under two Shared Socioeconomic Pathways: SSP126 (sustainability-focused, low emissions) and SSP585 (fossil-fuel-intensive, high emissions). These pathways

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incorporate consistent socioeconomic and climate narratives to account for projection uncertainties. Edaphic and topographic variables were acquired from the Harmonized World Soil Database (https://www.fao.org/soils-portal) and WorldClim, respectively. The variable selection process consisted of three steps: (1) preliminary screening through iterative runs in MaxEnt 3.4.4 using current occurrence data and environmental layers, retaining variables that contributed more than 0%, which reduced the variables from 37 to 24; (2) extraction of variable values at occurrence points via the “Sampling” tool in ArcGIS; and (3) collinearity assessment in SPSS 26 using Pearson correlation, excluding highly correlated variables ($|r| > 0.8$) that showed minimal contribution (Hao et al., 2024), which further reduced the variables from 24 to 16. The final refined variable set (16 variables) was used in subsequent modeling.

Maximum entropy model

The model was configured with the following settings: a 75%/25% split of training to testing data, 10,000 background points, a maximum of 1,000,000 iterations, and 10-fold cross-validation. Predictive accuracy was measured using the area under the receiver operating characteristic curve (AUC), where scores above 0.9 were considered to reflect high performance (Ren et al., 2020b). Variable importance was evaluated through Jackknife tests and response curve analysis. Model outputs, representing occurrence probabilities between 0 and 1, were binarized using a threshold of $p \geq 0.5$ to identify optimal environmental intervals, with adaptation thresholds determined from probability peaks (Zhang et al., 2023). Subsequent processing in ArcGIS 10.8 included: (1) conversion of ASCII results into raster format; (2) integration of projections using the Reclassify tool in Spatial Analyst; and (3) classification of habitat suitability according to Jenks’ natural breaks method, with categories defined as unsuitable (0 ~ 0.1), low (0.1 ~ 0.3), moderate (0.3 ~ 0.5), and high suitability (0.5 ~ 1) (Brismar, 1991). The extent of each habitat class was estimated based on grid proportions derived from reclassified attribute tables.

Centroid migration

The geographic centroids of potential habitats for *T. glandulifera* under different climate scenarios and timeframes were quantified using the “Mean Center” tool in ArcGIS 10.8. This analysis characterized both the centroid locations and their directional shifts, providing insight into the migration pathways of suitable habitats in response to climate change (Liu et al., 2018).

Results

Model evaluation

A Pearson correlation analysis conducted on 24 environmental variables identified 16 key environmental variables (*Fig. 2A*) that were used to construct the MaxEnt species distribution model (*Table 1*). Model performance evaluation revealed an AUC of 0.939 (*Fig. 2B*), with stable results from 10-fold cross-validation (standard deviation ± 0.024), significantly exceeding the random prediction level of 0.5. This outcome not only confirms the model’s excellent discriminative ability but also indicates that it maintains stable predictive performance across different data subsets, thereby providing a reliable foundation for subsequent ecological suitability analyses.

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Table 1. *Environmental variables*

Environmental variables	Name	Unit
BIO_12	Annual precipitation	mm
Elev	Elevation	m
BIO_7	Mean temperature of the wettest quarter	℃
BIO_11	Mean temperature of the coldest quarter	℃
T_clay	Topsoil clay content	%weight
Slope	Slope	°
T_ph_h2o	Topsoil pH	-log(H+)
BIO_3	Isothermality	/
Awc_class	Soil available water content	%
S_silt	Subsoil silt content	%weight
BIO_19	Precipitation of the coldest quarter	mm
T_silt	Topsoil silt content	%weight
BIO_15	Precipitation seasonality	/
S_caco3	Subsoil carbonate or lime content	%weight
Aspect	Aspect	/
S_sand	Subsoil sand content	%weight

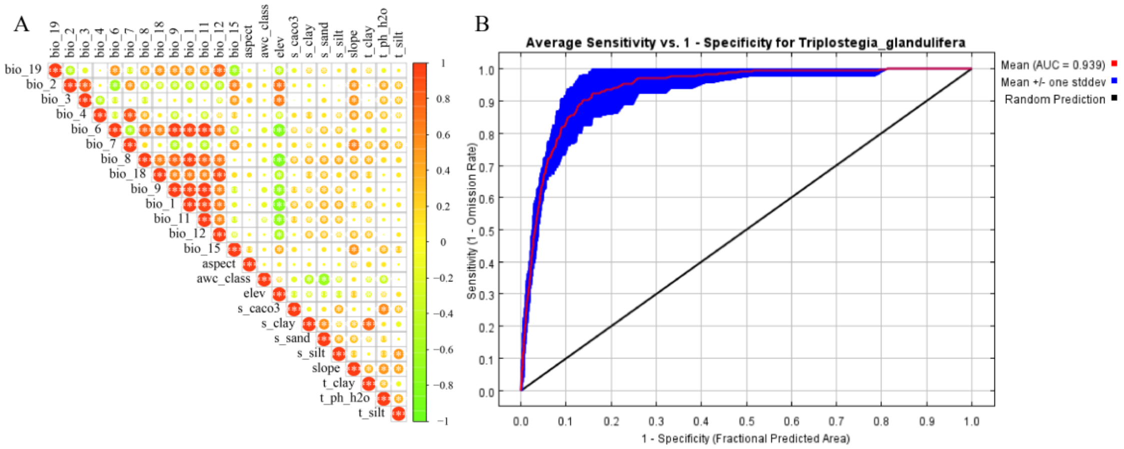

Figure 2. *Model evaluation: correlation analysis heatmap (A); ROC curve (B)*

Dominant environmental variables

Based on a comprehensive assessment of contribution rates and regularization training gains, this study identifies the dominant environmental variables influencing the distribution of *T. glandulifera*. Under current climatic conditions, annual precipitation (BIO_12), elevation (Elev), mean temperature of the wettest quarter (BIO_7), and mean temperature of the coldest quarter (BIO_11) collectively explain 74.2% of the model's variance (*Table 2*). Further validation using the jackknife method confirmed that these factors maintain high explanatory power when assessed independently (with training gains exceeding 0.6), indicating their stable and significant ecological driving effects on species distribution (*Fig. 3*). A comprehensive analysis reveals that the distribution of *T. glandulifera* is primarily regulated by the combined

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effects of water availability (represented by BIO_12) and temperature seasonality (illustrated by BIO_7 and BIO_11), while elevation further shapes its suitable habitat by influencing local water-heat redistribution. This finding elucidates the dominant environmental determinants of the species' distribution at a mechanistic level, providing a basis for understanding its ecological niche characteristics and potential responses to climate change in the future.

Table 2. *Environmental variables contributions*

Environmental variables	Name	Percent contribution (%)
BIO_12	Annual precipitation	26.7
Elev	Elevation	19.4
BIO_7	Mean temperature of the wettest quarter	18.9
BIO_11	Mean temperature of the coldest quarter	9.2

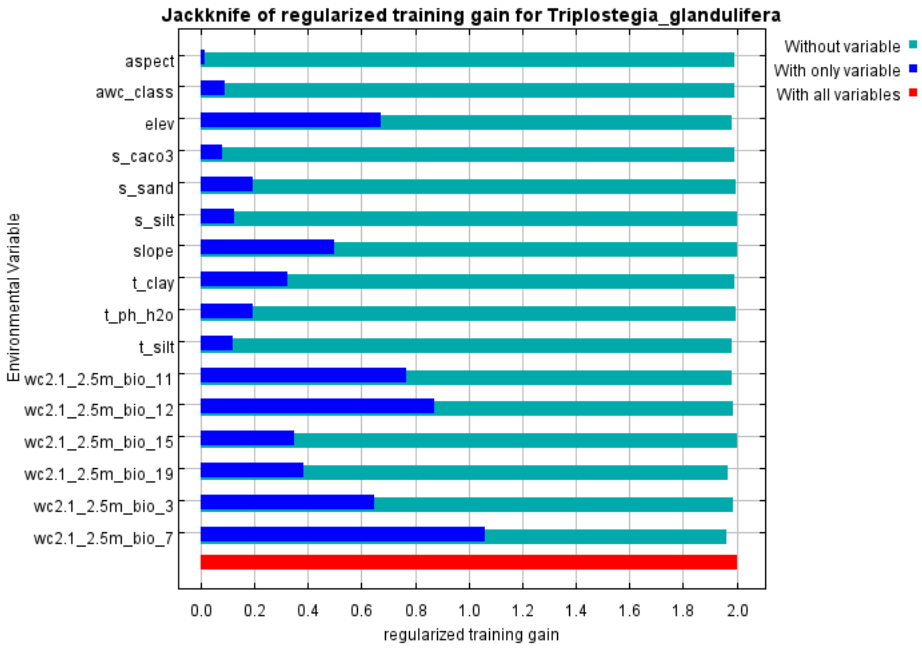

Figure 3. *Gain of each variable*

Response curve range

Based on the MaxEnt response curve analysis (*Fig. 4*; *Table 3*), the physiological tolerance range of *T. glandulifera* to environmental factors has been clarified. The adaptive threshold (optimal value) for each environmental variable was determined as the value corresponding to the peak of the response curve, indicating the condition under which the species has the highest probability of presence. Using a suitability threshold of a presence probability greater than 0.5, this species exhibits a high probability of survival within the ranges of annual precipitation (612.3 ~ 1262.3 mm), elevation (1618.4 ~ 4227.0 m), mean temperature of the wettest quarter (22.2 ~ 31.2°C), and mean temperature of the coldest quarter (-4.8 ~ 10.3°C). Although the absolute ranges of these variables are relatively broad, they represent a specific subset of the

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environmental gradients available across the study region, indicating that *T. glandulifera* occupies a constrained ecological niche. This niche specialization reflects its adaptation as a typical high-altitude, cold-adapted plant. Its distribution is strictly constrained by moisture conditions and temperature factors, while the elevation gradient further intensifies this limitation by modulating the water-heat combination. The findings reveal the species' specialized adaptive strategies to cold, humid habitats from a physiological ecological perspective, providing a mechanistic basis for predicting its future distribution dynamics.

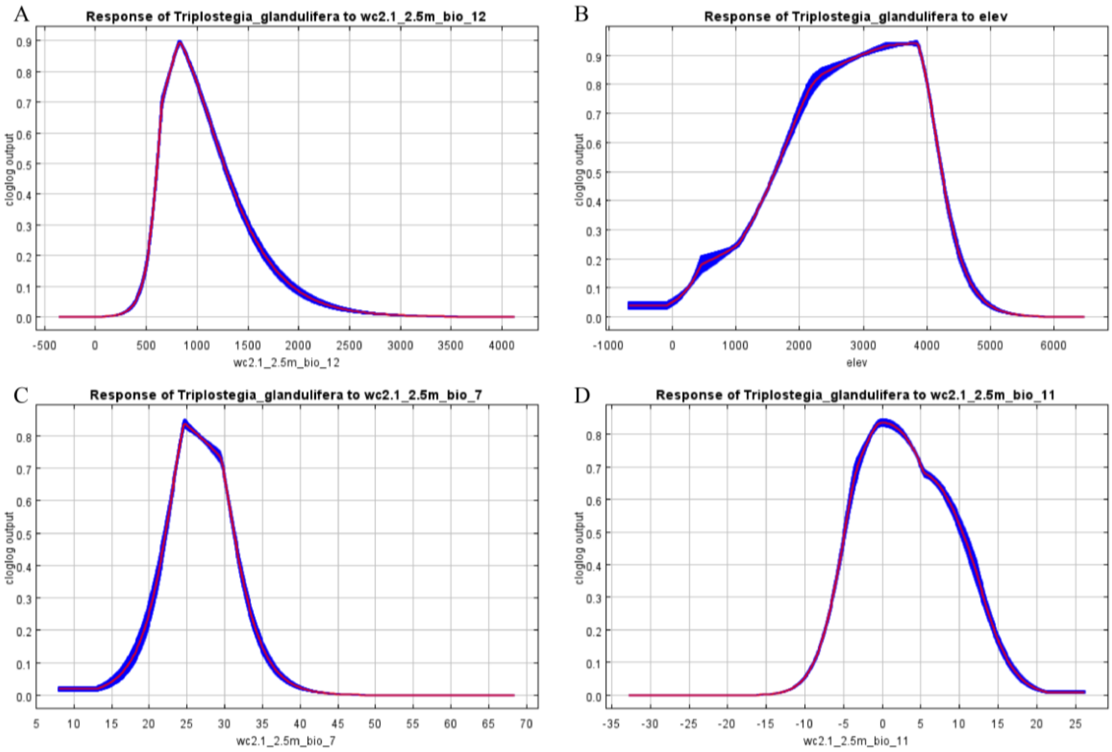

***Figure 4.** The response curve range: Annual precipitation (A); Elevation (B); Mean temperature of the wettest quarter (C); Mean temperature of the coldest quarter (D)*

***Table 3.** The response curve range*

Environmental variables	Suitable range	Adaptive threshold
BIO_12	612.3 ~ 1262.3 mm	831.9 mm
Elev	1618.4 ~4227.0 m	3840.0 m
BIO_7	22.2 ~ 31.2℃	24.7℃
BIO_11	-4.8 ~ 10.3℃	0.1℃

Current climate scenarios

The potential suitable distribution map for *T. glandulifera*, constructed using the MaxEnt model, indicates that the total area of suitable habitat is approximately 148.51 × 10^4 km^2. This distribution exhibits a gradient pattern, transitioning from southeast to northwest and from lower to higher elevations (*Fig. 5*). Spatial pattern analysis reveals

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that generally suitable habitats are widely distributed across several provinces in the central and eastern parts of the study area, while moderately suitable habitats display a transitional extension toward the southwestern inland regions. Notably, areas of highly suitable habitats exhibit a distinct ecological-geographical orientation, with their distribution extending continuously from the Hengduan Mountains to the southeastern edge of the Tibetan Plateau. The core regions of highly suitable habitats are concentrated in the central and western parts of Sichuan, northern Yunnan, and southeastern Tibet. This spatial structure not only confirms the species' specialized adaptation to cold, wet high-altitude habitats but also highlights the critical role of the Hengduan Mountains-Tibetan Plateau transition zone as a core distribution area and potential climatic refuge for the species.

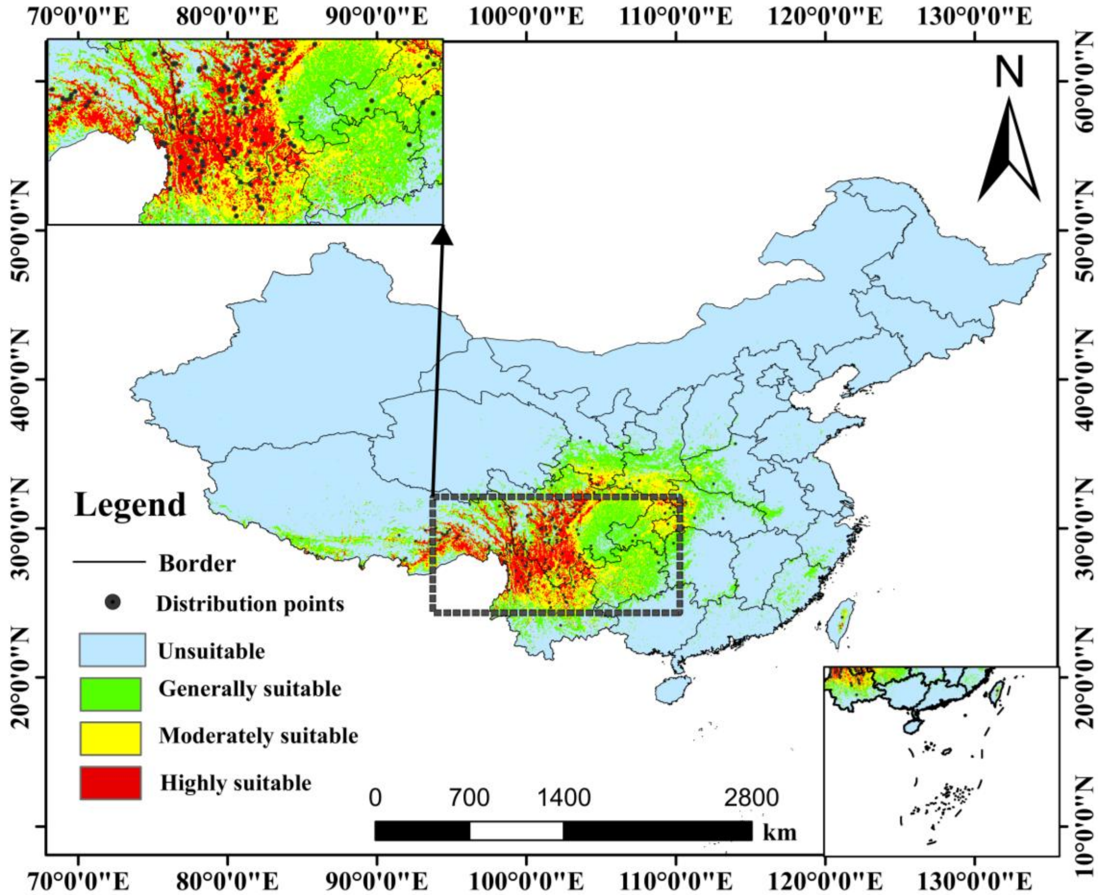

***Figure 5.** Potential distribution of T. glandulifera under current climate*

Future climate scenarios

In future climate scenarios, the suitable habitat patterns for *T. glandulifera* exhibit pronounced spatiotemporal differentiation (*Fig. 6; Table 4*). Under the SSP126 pathway, the total area of suitable habitat is projected to increase slightly by the 2050s compared to the present; however, significant internal restructuring occurs. Although the highly suitable areas expand slightly, there is a marked contraction of moderately suitable areas, indicating that the species' distribution may be concentrating towards more suitable core regions. By the 2090s, this trend becomes even more pronounced,

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with highly suitable areas further contracting in southwestern Sichuan, northwestern Yunnan, and southeastern Tibet, suggesting that these regions will become critical refuges for the long-term survival of the species. In contrast, the SSP585 high-emission scenario presents a different evolutionary trajectory: while the total area of suitable habitat peaks in the 2050s, it experiences a significant decline by the 2090s. Although there is some localized expansion of highly suitable areas, the overall distribution becomes more fragmented. Both scenarios indicate that the ecological transition zone from the Hengduan Mountains to the southeastern edge of the Tibetan Plateau consistently maintains highly suitable habitats, highlighting its crucial role as a core distribution area and future refuge for this species. These findings not only reveal the quantitative impacts of climate change on species distribution ranges but also qualitatively explain the reconfiguration processes of their distribution patterns, providing a scientific basis for the development of targeted conservation strategies.

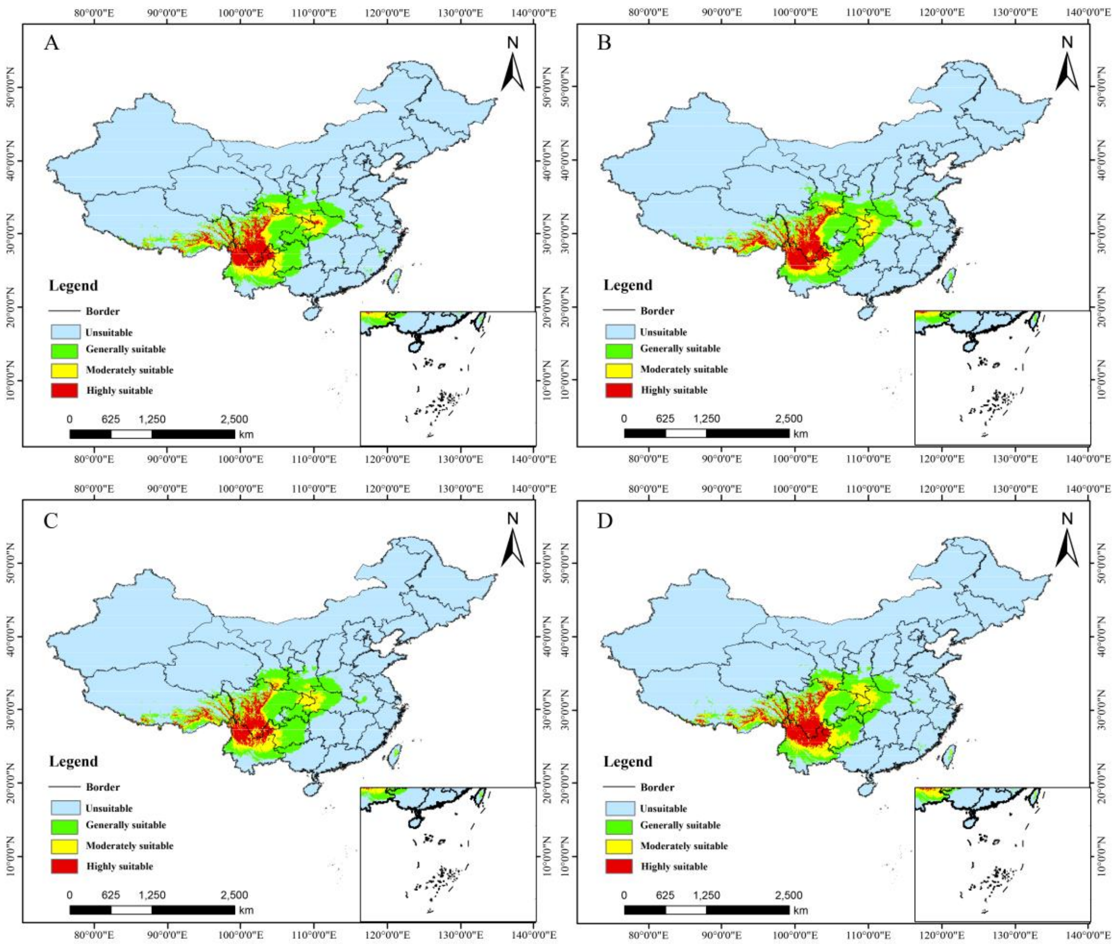

Figure 6. *Potential distribution of T. glandulifera under future climate: 2050s, SSP126 (A); 2090s, SSP126 (B); 2050s, SSP585 (C); 2090s, SSP585 (D)*

Centroid migration

In future climate scenarios, the centroid of suitable habitat for *T. glandulifera* exhibits a significant migration trend with ecological implications (*Fig. 7*; *Table 5*).

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Compared to the current centroid location (102.72°E, 29.37°N), both scenarios demonstrate a notable shift towards the northwest (SSP126: 410.92 km; SSP585: 422.47 km), indicating that the species may seek suitable habitats at higher elevations in response to climate change. Notably, under the SSP585 scenario, the centroid shows a retreat of 434.18 km towards the southeast in the long term, suggesting that under severe climate stress, the species' distribution may be forced to contract towards historical refugia, such as the Hengduan Mountains. These migration patterns collectively reveal the species' response strategy to climate change: prioritizing expansion into higher elevation areas to the northwest, but retreating to ecologically stable traditional habitats when climate stress exceeds ecological thresholds. This finding provides spatial evidence for understanding species distribution dynamics and their adaptation mechanisms, as well as a scientific basis for the dynamic delineation of priority conservation areas.

Table 4. *Suitable area of T. glandulifera under different scenarios and periods*

Periods	Scenarios	Highly suitable (× 10^4 km^2)	Moderately suitable (× 10^4 km^2)	Generally suitable (× 10^4 km^2)	Total suitable area (× 10^4 km^2)
Current		26.42	45.60	76.49	148.51
2050s	SSP126	29.52	40.04	86.98	156.54
	SSP585	29.90	41.90	85.54	157.34
2090s	SSP126	28.96	40.49	88.26	157.71
	SSP585	31.65	41.75	78.42	151.82

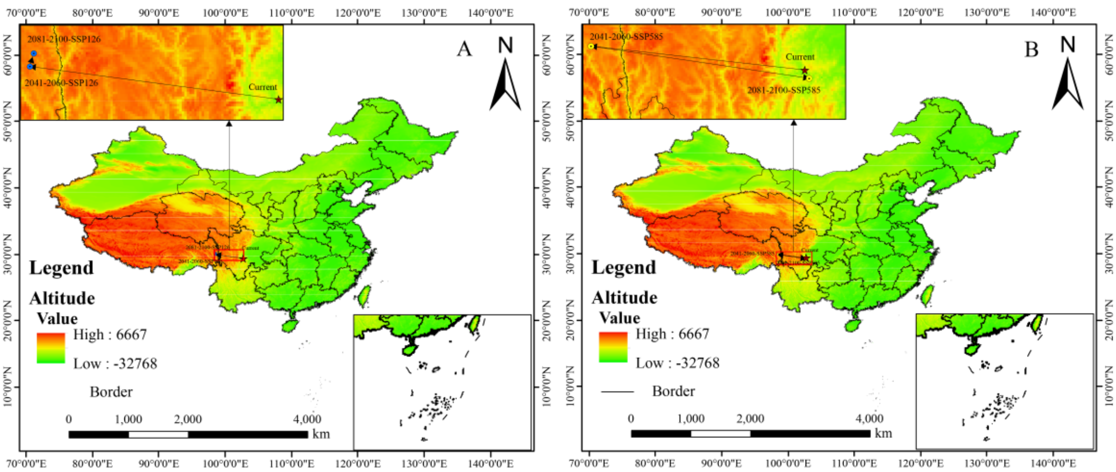

Figure 7. *Centroid migration routes: 2050s -2090s, SSP126 (A); 2050s -2090s, SSP585 (B)*

Table 5. *Centroid migration routes of T. glandulifera*

Climate scenarios	Periods	Longitude (°E)	Latitude (°N)	Migration distance (km)
	Present	102.72	29.37	
SSP126	2050s	98.52	29.93	410.92
SSP126	2090s	98.58	30.15	25.66 (2050s to 2090s)
SSP585	2050s	98.39	29.86	422.47
SSP585	2090s	102.81	29.21	434.18 (2050s to 2090s)

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Discussion

This study systematically predicted the potential geographic distribution of *Triplostegia glandulifera* by integrating multi-source distribution data and environmental variables using the MaxEnt model. The model evaluation results indicated an AUC value of 0.939, with a small standard deviation (±0.024) from tenfold cross-validation, demonstrating the model's excellent discriminative ability and robust predictive performance (Fuster-Alonso et al., 2025). This high performance not only meets the conventional standard of "high accuracy" in species distribution models (AUC > 0.9) but also suggests that the 75%/25% training-testing data split, tenfold cross-validation, and background point selection strategies employed in this study effectively ensured the model's stability across different data subsets (Steen et al., 2024). Notably, recent research has emphasized that relying solely on the AUC metric may overestimate performance; therefore, independent validation and error analysis using external datasets are necessary to enhance model reliability and accuracy (Matutini et al., 2021). Furthermore, this study employed the jackknife method and response curve analysis to identify BIO_12, Elevation, BIO_7, and BIO_11 as the dominant environmental variables influencing the distribution of *T. glandulifera*. This finding aligns closely with the mechanisms of species distribution regulated by hydrothermal synergy as described in niche theory (Chi et al., 2024).

The results indicate that the high suitability areas for *T. glandulifera* are predominantly located from the Hengduan Mountains to the southeastern edge of the Tibetan Plateau. This region, recognized as an important biological refuge during the Quaternary glaciation (Wang et al., 2023), has long been considered a center for the evolutionary persistence of various alpine plants (Han et al., 2022; Ren et al., 2020a). Model analysis further identified annual precipitation (BIO_12), elevation (Elev), and the mean temperature of the wettest quarter and the mean temperature of the coldest quarter (BIO_7 and BIO_11) as the four dominant environmental factors affecting the distribution of this species, collectively explaining 74.2% of the model variance. This result is corroborated by several ecological studies on alpine plants. For instance, research on *Stipa purpurea* in the Tibetan Plateau region similarly identified annual precipitation and elevation as dominant variables, with temperature factors serving as critical auxiliary drivers, collectively supporting the species' conservative adaptation strategy to climate gradients (Ma and Sun, 2018; Liu et al., 2016) and further validating the synergistic role of hydrothermal factors in the construction of alpine plant niches. Although soil factors were not identified as dominant predictors in this study, possibly due to the coarse resolution of available soil data or their relatively weaker influence at the macro scale, they may play a more important role at the local habitat scale. Future studies incorporating higher-resolution soil property data (e.g., soil nutrients, texture) could further elucidate the potential influence of soil factors on species distribution.

T. glandulifera exhibits specialized adaptive traits to high-altitude habitats (1618.4 ~ 4227.0 m), moderate precipitation levels (612.3 ~ 1262.3 mm), and low temperatures (mean temperature of the coldest quarter ranging from -4.8 to 10.3°C). Its relatively specialized ecological niche, defined by specific ranges of precipitation, elevation, and temperature, is characteristic of many alpine plants in the Hengduan Mountains. This study further reveals that under future climate scenarios, the centroid of suitable habitats for this species is projected to migrate upward, aligning with the global trend of alpine plants shifting to higher elevations in response to climate warming (Wang et al., 2025b). However, the migration capacities of different species vary significantly. For instance,

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in the Himalayas, the Himalayan fir (*Abies spectabilis*) is highly sensitive to temperature changes, exhibiting a tree line migration rate of approximately 1.1 m per year, which is considerably higher than that of the moisture-dependent *Betula utilis*, which migrates at about 0.6 m per year (Sigdel et al., 2024). The migration dynamics of *T. glandulifera* under the SSP585 scenario, particularly the later retreat towards the southeast (core region of the Hengduan Mountains), may reflect its adaptation strategy of retreating to historical refugia due to limitations imposed by dispersal capacity or interspecific competition under intense climatic stress.

Although model predictions indicate that the overall suitable area for *T. glandulifera* may remain relatively stable in the future, significant reorganization of its spatial distribution is expected. Specifically, the distribution centroid is projected to shift towards higher elevations in the northwest, while under high-emission scenarios such as SSP585, some populations may retreat southeast to historical refugia like the Hengduan Mountains. This "expansion-retraction" dual-phase response pattern underscores the critical ecological buffering role of the Hengduan region (Liu et al., 2023; Tang et al., 2024). It is important to note that the upward shift of forest tree lines driven by climate warming may further constrain the suitable habitat for alpine plants (Winkler et al., 2019). Consequently, in areas where the potential distribution of *T. glandulifera* overlaps with the tree line transition zone, it is essential to monitor the potential interspecific competition and niche compression effects that may arise from future shifts in vegetation zones, in order to develop more proactive conservation strategies.

Based on the aforementioned research findings, we propose the following targeted conservation strategies to effectively ensure the long-term survival and ecological security of *T. glandulifera*, a species adapted to high-altitude and low-temperature environments. Firstly, we recommend designating the current core area of its high suitability zone—specifically, the ecological transition zone from the Hengduan Mountains to the southeastern edge of the Tibetan Plateau—as a priority conservation area. This area should be subject to regular monitoring and focused protection to maintain the integrity of existing high-quality populations and their habitats. Secondly, ecological corridors should be established along the predicted northwest migration pathways to facilitate the natural migration and gene flow of this species to higher altitudes in response to climate change. Furthermore, we suggest the creation or expansion of nature reserves in identified conservation gaps, such as the middle and lower reaches of the Yarlung Tsangpo River Valley and the southeastern Hengduan Mountain Valley on the Tibetan Plateau, to form a comprehensive conservation network that covers the entire distribution range of *T. glandulifera*. This study, which simulates the distribution dynamics of *T. glandulifera* under current and future climate conditions, reveals its ecological niche characteristics strictly regulated by water and thermal factors, as well as a dual-phase "expansion-retraction" response pattern. These findings not only deepen our understanding of the adaptive mechanisms of alpine plants but also provide crucial scientific evidence for developing a systematic conservation plan centered on refuge protection, while also considering migration pathways and potential expansion areas.

Conclusions

This study systematically predicts the potential geographic distribution of *Triplostegia glandulifera* under current and future climate conditions. The results

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indicate that its distribution is primarily regulated by water availability (annual precipitation) and temperature seasonality (mean temperatures of the wettest and coldest quarters), while elevation further shapes the suitable range through local water-heat redistribution. Currently, highly suitable areas are concentrated in the southeastern edge of the Hengduan Mountains and the Tibetan Plateau, which serves as both a core area for existing distribution and a historical climate refuge. In the future, suitable areas are expected to shift northwestward to higher elevations, and under the SSP585 scenario, some populations may retreat to the Hengduan Mountains, resulting in a dual-phase response pattern characterized by “expansion-retraction.” Based on these findings, it is recommended to implement focused conservation efforts in the transitional zone of the Hengduan Mountains and the Tibetan Plateau, establish ecological corridors along the northwest migration path, and enhance the network of nature reserves in underprotected areas such as the middle and lower reaches of the Yarlung Tsangpo River. This approach aims to create a systematic conservation strategy that encompasses existing habitats, migration corridors, and potential expansion areas, thereby providing a scientific basis for the climate adaptation of alpine plants.

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